Technical Report No. 32-657

Methods for Obtaining Velocity and Range Information from CW Radars

Mahlon Easterling

JET PROPULSION LABORATORY
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Mahlon Easterling

Walter K. Victor

Walter K. Victor, Chief
Telecommunications Division

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Continuous wave radars are particularly suited for obtaining velocity and range information on single targets at extreme ranges whether they be spacecraft in orbit about the earth or enroute to the Moon or another planet, or natural celestial bodies such as the Moon or inner planets. The carrier itself provides the means for determining the velocity of the target because of the doppler shift of the returned signal. Ways of measuring this doppler shift for both coherent and noncoherent returned signals are discussed. The determination of range requires that the carrier be modulated. Methods of deriving modulating waveforms from pseudo-random sequences which are suitable for achieving high resolution and accuracy and resolving ambiguity are given, as well as ways of extracting the range from a returned signal. Techniques are described for both the coherent and noncoherent carriers. The several techniques described have all been embodied in actual radar systems and used to track appropriate targets. Experimental results are given to show the performance which can be attained.

Author

I. INTRODUCTION

Continuous wave (CW) radars are particularly suited to tracking spacecraft because the same carrier can also be used for communications. The presence of a carrier allows narrow band detection methods to be applied to both functions. A factor that has contributed to the rapid development of these radars is that their operation is inherently the same with or without a transponder. Therefore, much of the development work has been done using passive reflectors, for example the Moon and inner planets.

The most useful kinds of tracking information which can be obtained by radar from very distant targets are radial velocity and range. The carrier in a CW radar provides a direct means for determining the radial velocity by measuring the doppler shift. To obtain range information, it is necessary to modulate the carrier and use the returned modulation to determine the round trip propagation time for the signal. This *time of flight* is related to the range by the propagation velocity.

The CW radars to be discussed may be divided into two classes according to whether or not the returned signal is coherent, or, more to the point, whether it can be treated as coherent by the receiver. In the discussion which follows the velocity measuring methods are treated first, both the coherent and noncoherent cases. Results of actual tracking operations are given as each method is discussed. The treatment of methods for measuring range begins with a development of the theory of the modulating signal derived from pseudo-random sequences. This is followed by methods applicable to the coherent radar and to the noncoherent radar. Results are given for each method as it is presented. Since many of the techniques presented here were developed at the Jet Propulsion Laboratory (JPL) for the National Aeronautical and Space Administration (NASA)/JPL Deep Space Instrumentation Facility (DSIF), the descriptions of the techniques apply to an L-band or S-band radar, and the results are also for these frequencies. However, by a suitable adjustment of parameters, the techniques are applicable at other frequencies.

II. VELOCITY MEASUREMENT WITH A COHERENT CW RADAR

A doppler measuring coherent CW radar is shown in Fig. 1 in simplified form. Note that in this figure and in others to follow, many absolutely vital parts of the radar are omitted. There will be no discussion of antennas, feeds, masers, transmitters, and other parts which are both necessary and of great interest. Suffice it to say that appropriate devices of this sort were used in the examples to follow and were necessary for the overall operation of the system.

In Fig. 1, it is assumed that the target is passive. A CW signal derived from a frequency standard is transmitted to the target and reflected to the receiver. The receiver tracks the phase of the received signal and produces an output which is a filtered version of the input. This output, which is shifted in frequency by the doppler effect, is mixed with the transmitted frequency and the difference frequency counted. Since the receiver tracks the phase of the returned signal there is no frequency error as such; errors due to noise appear as jitter in the measurements, but there is no bias. This permits statistical methods to be applied to smooth the measurements.

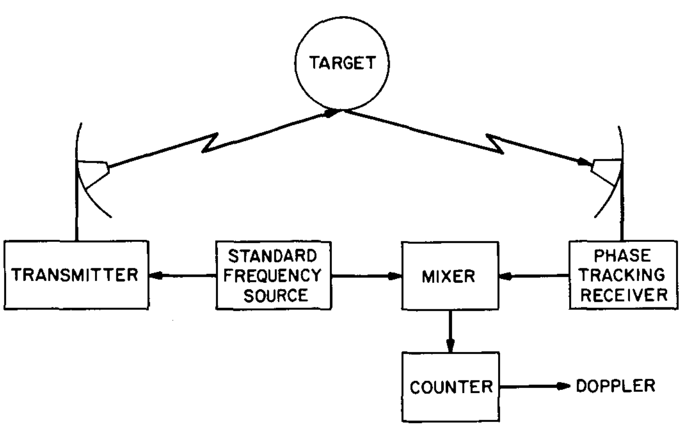

Fig. 1. Doppler measurement by coherent CW radar

An early application of this technique was in the tracking of the Echo I balloon satellite (Ref. 1 and 2) and in tracking experiments on the Courier satellite (Ref. 3). In regard to the Courier satellite, a full tracking and orbit determination experiment was performed, but the target was treated as a passive device; no use was made of the on-board electronics. A block diagram which shows the form of the receiver and the way in which the mixing is done is given in Fig. 2.

In this system, the two antennas were separated by some 7 mi and two ranges of mountains to provide isolation. A microwave communications link was used to provide a coherent reference for detecting the doppler shift on the received signal. The receiver was a double superheterodyne phase-locked loop. The extra heterodyning signals are derived from the coherent reference and a free running 455 kc oscillator, but the free running oscillator is used in such a way that its frequency does not enter into the output. The actual doppler as detected and counted was 75/80 of the doppler on the returned signal. The somewhat unusual frequencies used in the system were selected for ease of mechanization and to combat leakage problems.

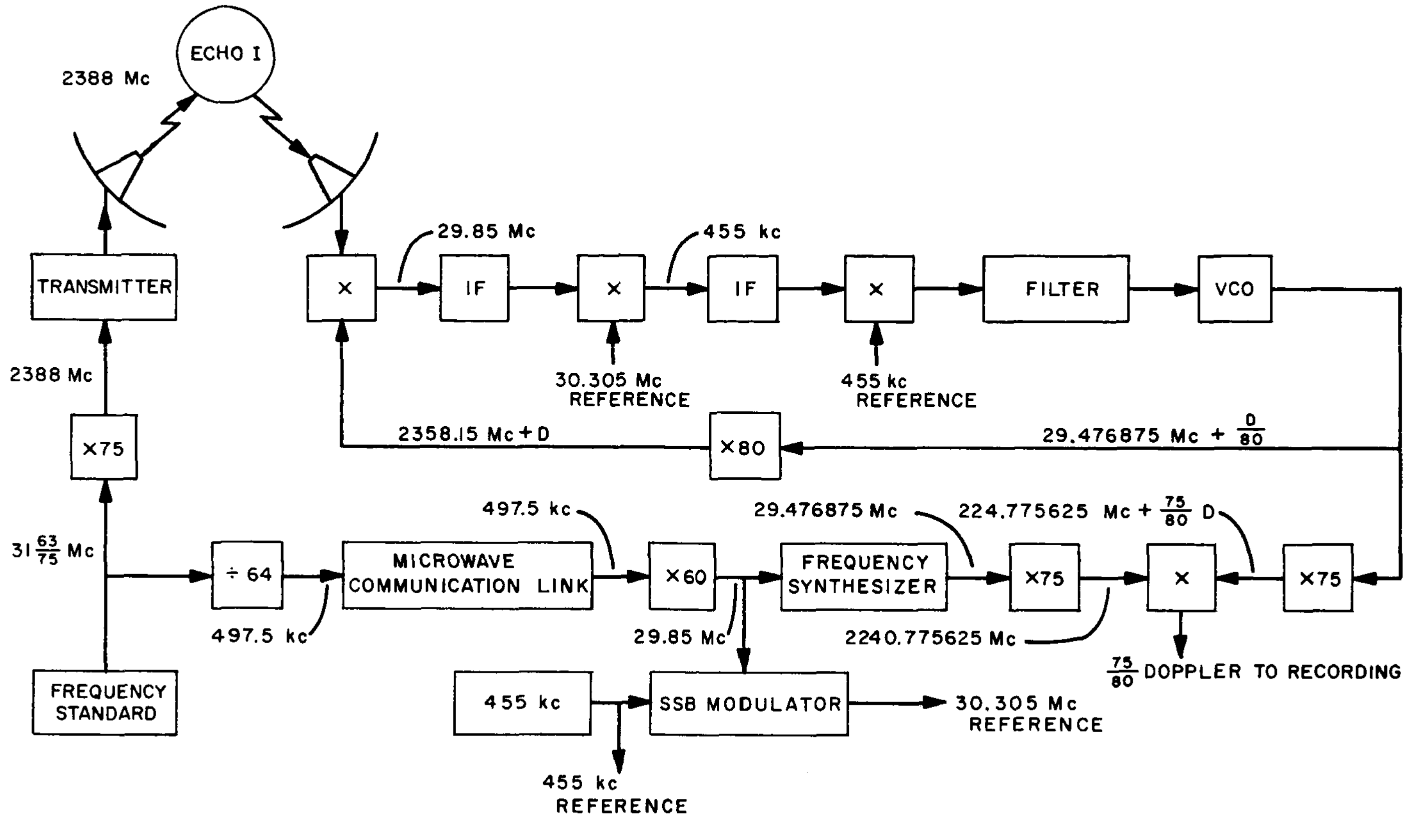

Fig. 2. Velocity tracking used for Echo I

The system shown in Fig. 2 is inherently capable of detecting a change in propagating path length of one wavelength of the carrier (times 80/75) or about 13.5 cm. If the doppler frequency is counted for 1 sec the velocity resolution is 6.75 cm/sec. If the frequency is counted for a longer time the resolution theoretically increases. Actually, the useful resolution is limited by the stability of the system and the accuracy and stability of the frequency standard. In tracking the Courier satellite, the doppler was counted for 1 sec every 2 sec and an attempt was made to determine the accuracy of the tracking data by comparing them with a *best fit* orbit. The rms velocity residual compared to the orbit was 9.4 cm/sec but other evidence indicates that a part of this discrepancy was due to the orbit determination program. Any mathematical model used for computing an orbit necessarily contains many simplifying assumptions and a number of constants pertaining to the geometry of the situation. The velocity residual contains these effects as well as the effects of errors in tracking (Ref. 3).

The technique used to measure the velocity of a passive target can be extended to an active target, i.e. a target which includes a transponder. Ideally, the transponder would be a reflector with power gain. Practically, it is necessary to receive on one frequency and transmit on another. This can be accomplished by using a phase tracking receiver in the transponder and deriving the transmitter signal from the output of the receiver. If, in addition, all heterodyning frequencies are also derived from the output of the receiver, the transmitted signal is coherent with the received signal. The frequency of the transmitted signal is a constant times the frequency of the received signal. This apparent increase in complexity can be turned to advantage in the radar itself. Since the transmitter and receiver are at different frequencies, they can be diplexed on the same antenna. Since the antennas are large and expensive, this is a distinct advantage. The disadvantage is that the doppler equation is more complex, but since the tracking data is usually reduced by large computers, this is not important.

The *Ranger* and *Mariner* spacecraft have used a coherent transponder of the form shown in Fig. 3. The output frequency is exactly 96/89 times the input frequency.

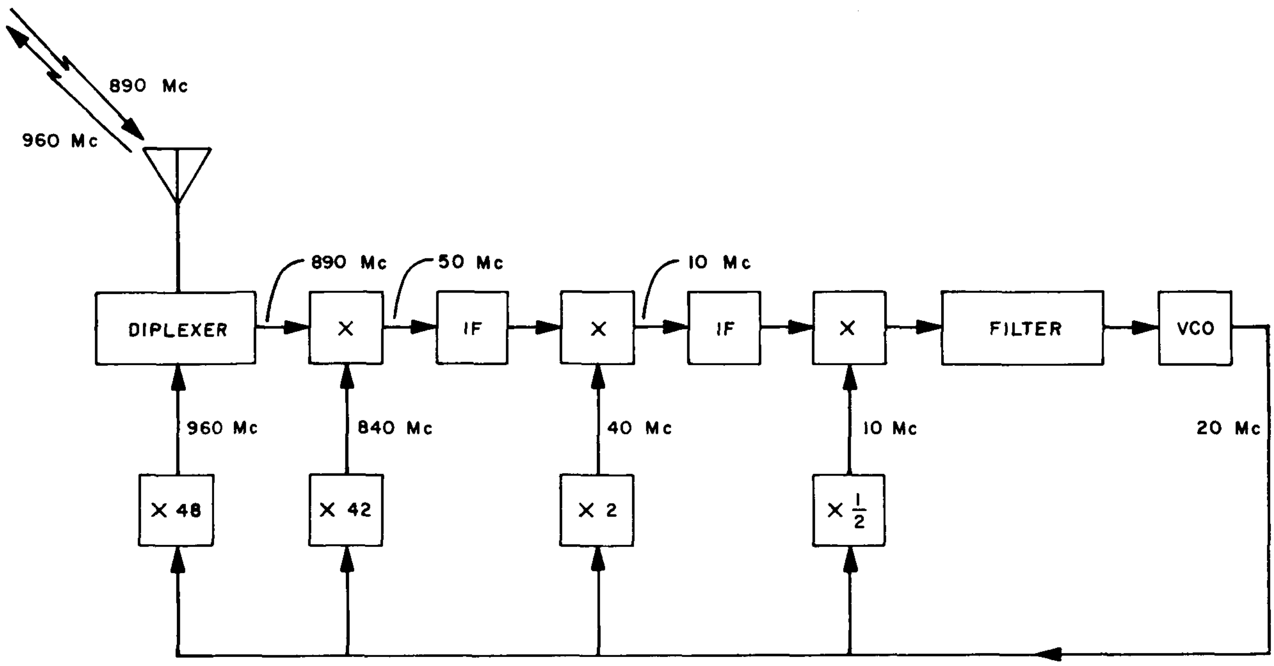

Fig. 3. ***Ranger-Mariner* transponder**

The overall doppler measuring system is shown in Fig. 4. The transmitter and receiver are very much the same as those in Fig. 2 except that different frequencies are used. The doppler measuring system is different from that previously shown in two ways. One difference is that the signal is first detected at the VCO frequency and then multiplied to give the doppler instead of being multiplied before detection. The result is the same. The other difference is that the doppler frequency is deliberately biased by introducing an offset into the reference to facilitate counting, since the counted frequency never becomes zero. There is no effect on the accuracy of the system (Ref. 4).

When the *Mariner II* spacecraft to Venus was being tracked, the usual frequency standard at the tracking stations was a high quality crystal oscillator. This standard proved to be the limiting factor in the accuracy of the doppler measurement. The doppler was counted for 50 sec each 60 sec. When the propagation time to the spacecraft and back was 20 sec, the rms error in velocity compared to a best fit orbit was 7.5 cm/sec. One tracking station, Goldstone, was fitted with a rubidium vapor frequency standard. When the propagation time to the spacecraft and back was 58 sec, the rms error in velocity compared to a best fit orbit was only 0.3 cm/sec. This extreme accuracy can now be obtained in routine operation.

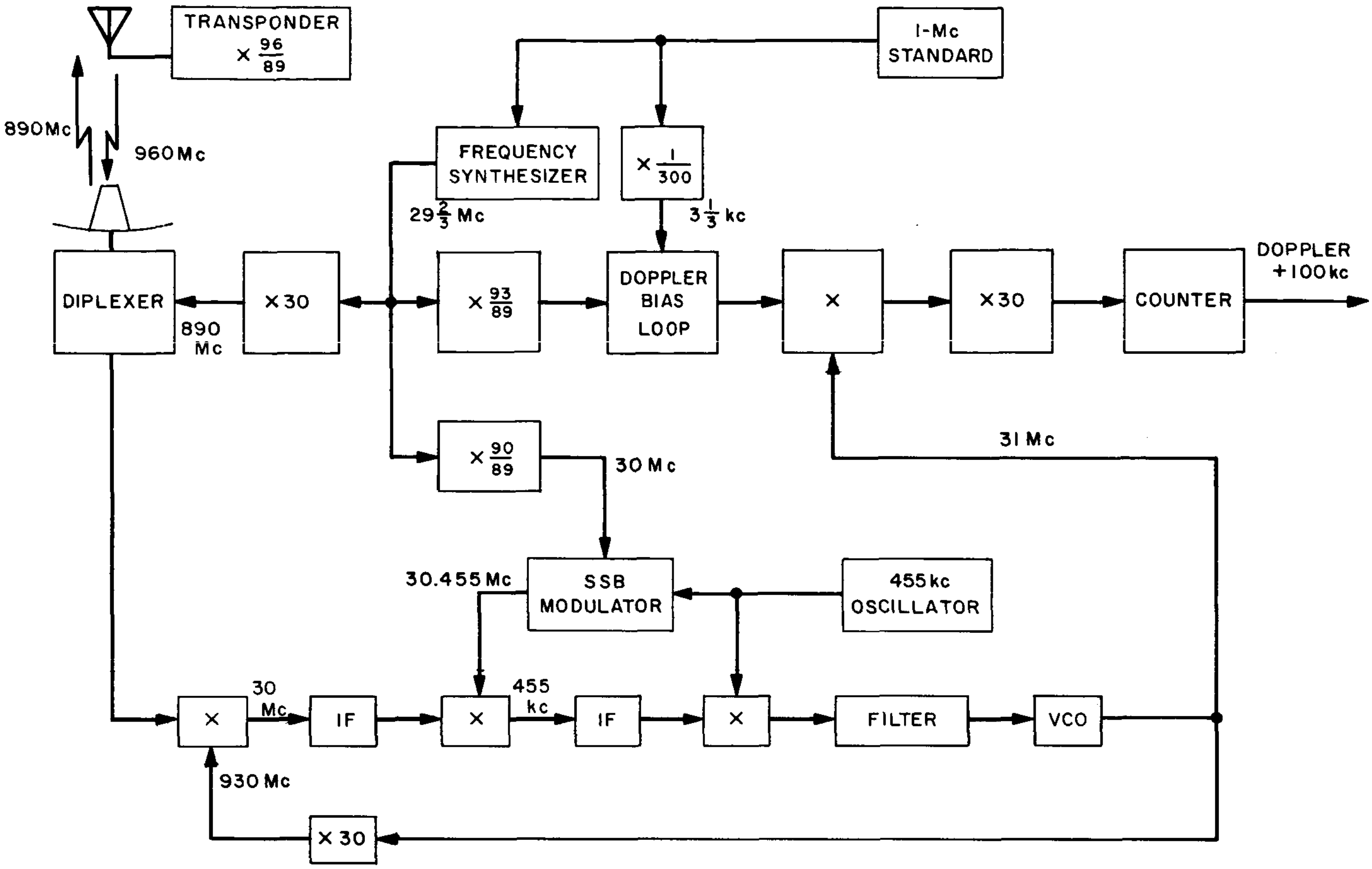

Fig. 4. *Ranger-Mariner* radar

III. VELOCITY MEASUREMENT WITH A NONCOHERENT CW RADAR

The noncoherent CW radar has been developed to overcome certain limitations of the coherent CW radar. These limitations are of two kinds; there is a minimum signal level which can be tracked, and the coherent receiver is inherently unsuited to the reception of certain kinds of noncoherent signals. The receiver in the coherent radar is a kind of phase-locked loop and is essentially a linear filter. As such, it can be made optimum in a Wiener sense, and, because it tracks, can be made very narrow band. However, it has a threshold below which it loses lock and a minimum bandwidth determined by the self noise of the oscillator in the loop. Thus, there is a lower limit of signal level which can be tracked. Typically, the minimum bandwidth is a few cycles per second and the threshold occurs when the signal power is equal to the noise power in the loop bandwidth.

The coherent radar has been used with targets which return a noncoherent signal, e.g. the Moon and Venus, and it appears to track the center of the returned spectrum. However, the analysis of the tracking process with the odd statistics of these signals is difficult and not yet completed.

The noncoherent CW radar uses a receiver which is a kind of spectrum analyser. No attempt is made to track

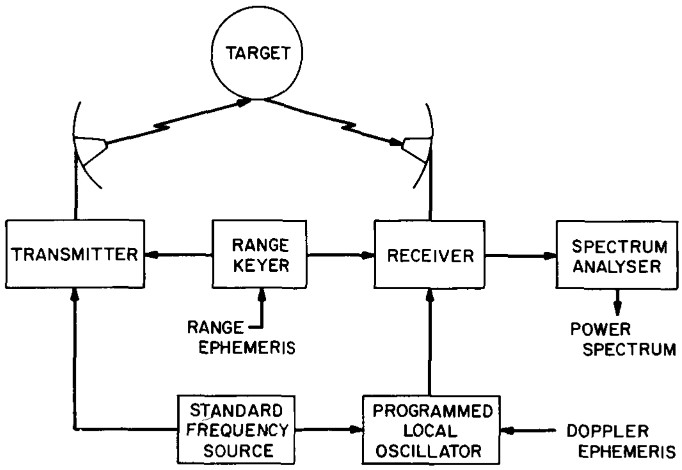

Fig. 5. Noncoherent CW radar

the returned signal, rather the signal is processed to determine the power spectrum. The form of the radar is shown in Fig. 5 with a passive target. A standard frequency is transmitted to the target and reflected back to the receiver. In general, the returned signal is shifted in frequency by the doppler effect and spread in frequency by the reflecting characteristics of the target. A special feature of the receiver is the programmed local oscillator. This is a device which uses an ephemeris to automatically tune the local oscillator to remove the doppler shift from the returned signal. An ephemeris is essentially the best estimate of the path of the target to be tracked. In the case of a celestial body or a spacecraft at an extreme distance, the ephemeris is usually quite good, at least good enough to tune the received signal into the range of the spectrum analyser and keep changes in frequency from blurring the spectrum while it is being measured.

The spectrum analyser itself is in two parts: a digital device which computes the autocorrelation function of the received signal continuously in real time and a small digital computer which computes the Fourier transform of the cummulative autocorrelation function whenever a power spectrum is desired.

Since the digital devices are not subject to drift, the spectrum may be determined for a signal of any desired duration. The ability to determine the spectrum of a returned signal over a long period of time is made useful by the fact that the spectrum analyser is arranged to overcome the effects of noise. This is accomplished by operating the radar as a Dicke radiometer. The transmitter is turned on and off for short intervals of time, typically 1 sec. The receiver determines the spectrum of the returned signal plus noise when there is a returned signal and of noise only when there is no returned signal. The best estimate of the signal spectrum is then the difference of the two spectra. The receiver must, of course, be told when to expect a signal. This is the function of the device labeled range keyer in Fig. 5. Note that errors in the range ephemeris cause a loss in signal power, about 2%/1000 mi or range error when a 1 sec on and off period is used. Ordinarily the distance to the celestial bodies and to spacecraft is known to within a few thousand miles.

The noncoherent CW radar does not suffer from the limitations given above for coherent CW radars. Signals have been detected at least 15 db below the threshold of the best coherent receivers known. In addition, the spectra from certain bodies, e.g., Venus, are not symmetrical. There are often prominent features on one side or the other which persist for several days and move slowly across the spectrum, apparently as the planet rotates. The presence of such an asymmetry certainly introduces a bias into the doppler measurement as made by a phase-locked receiver. With the spectrum analyser, the location of the central peak of the spectrum can usually be determined. Where the central peak is distorted by a feature close to the center, the shape of the spectrum shows this and the velocity measurement from the spectrum can be discarded.

A more detailed diagram of the radar used in the JPL 1964 Venus experiment is shown in Fig. 6. Note that a single antenna is used in this radar, not by diplexing, but by time sharing. Since the time required for a signal to propagate to Venus and back is a number of minutes, the antenna is used for transmitting for one round trip followed by one round trip time for receiving. The switchover time is a small portion of the round trip time. The spectrum analyser is stopped during the transmit portion of the cycle, but the information is not destroyed. The nature of the spectrum measurement allows the use of noncontiguous pieces of signal. Being able to use one antenna is a distinct advantage.

In the system of Fig. 6, the frequency source is an atomic oscillator with an accuracy of a few parts in 10^{11}, and the programmed local oscillator is capable of tuning to within ¼ cps at the received frequency.

Figures 7 and 8 give an indication of the range in signal level which may be handled by the radar. Figure

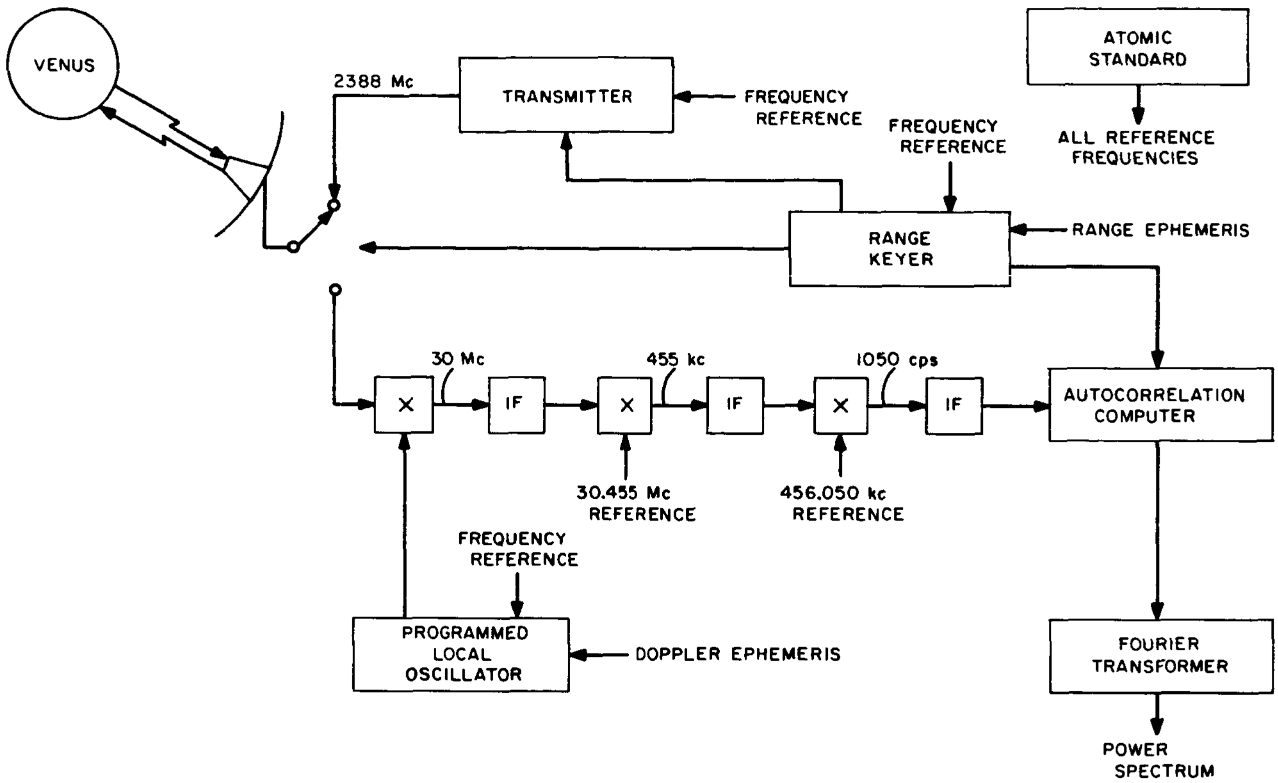

Fig. 6. 1964 Venus radar system

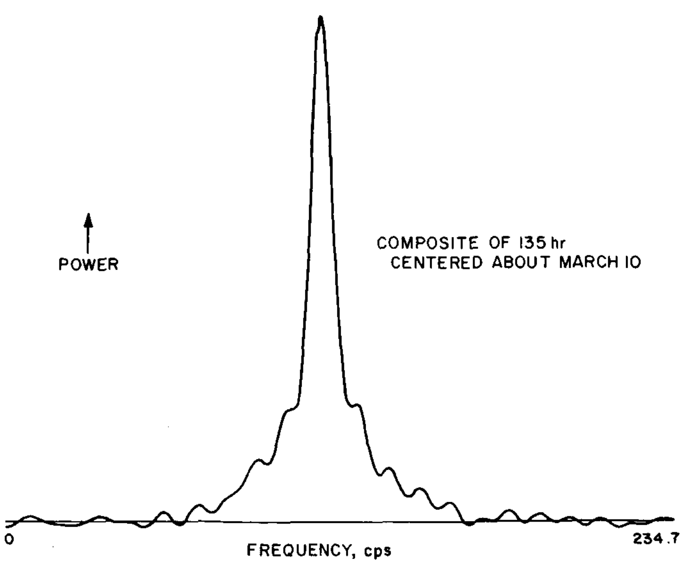

Fig. 7. Venus power spectrum — long duration

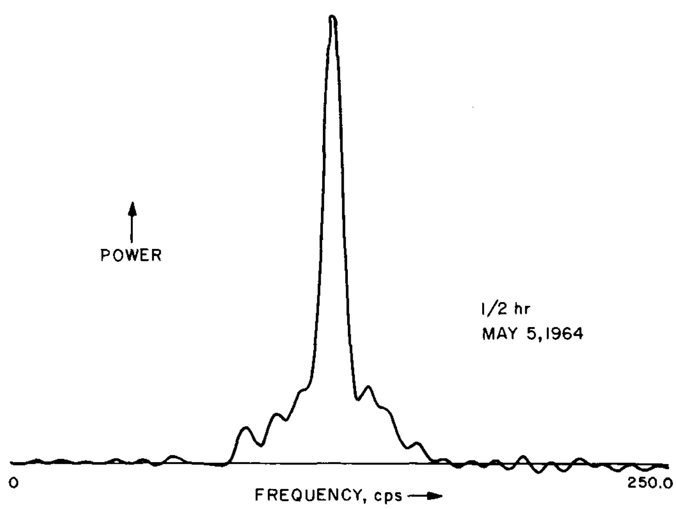

Fig. 8. Venus power spectrum — short duration

7 is a spectrum of the return from Venus using 135 hr of signal. Figure 8 is a spectrum taken when Venus was much closer and using only ½ hr of signal. The resolution of the spectrum can be adjusted by adjusting the sampling rate of the device which computes the autocorrelation function. Since an increased resolution requires a slower sampling rate, the limitation on the resolution is set by the local oscillator rather than the spectrum

analyser and a ¼ cps is the limit achieved. This implies that the radar is able to distinguish increments in velocity of 1.6 cm/sec. However, this requires that the ephemeris be smooth to this amount which poses some special problems in computing.

All in all, it is probably fair to say that the accuracy with which radar can measure velocity is about 6 cm/sec. However, the measurement is unbiased so that a number of measurements can be smoothed together, for example by fitting an orbit.

IV. THEORY OF PSEUDO-NOISE RANGING

A radar determines range by measuring the time required for a signal to propagate to the target and return. This may be done in a CW radar by modulating the transmitted signal with a suitable periodic waveform, recovering the modulation from the returned signal, and measuring the phase of the returned modulation relative to the phase of the transmitted modulation. This phase difference is a measure of the round trip propagation time and, therefore, of the range. Because the carrier is continuous, the modulation may be continuous; the receiver can be arranged to track the modulation, and the phase measurement can be made continuously to yield a continuous determination of range. Figure 9 is a simplified diagram of such a system. Note that the modulation waveform is timed by a frequency standard. This assures that the phase measurement, which is in terms of the period of the transmitted modulation, is an accurate representation of the round trip time.

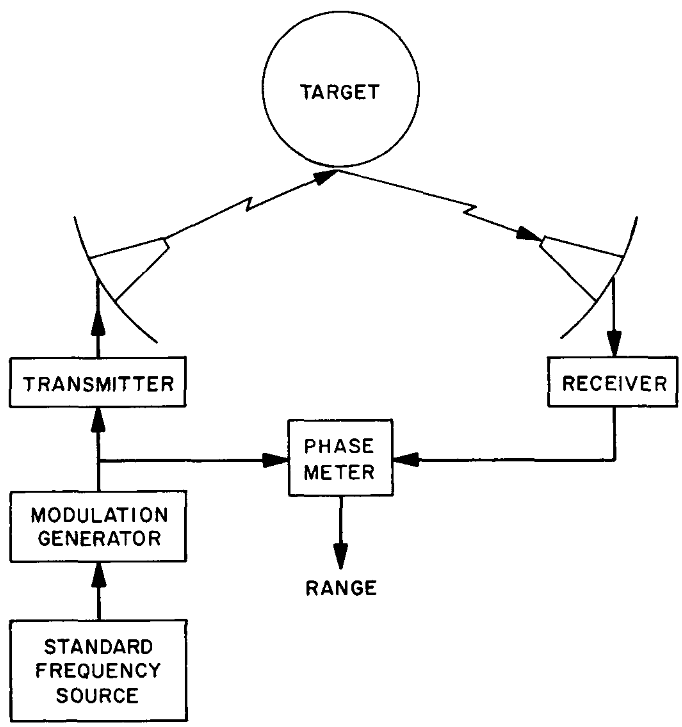

Fig. 9. CW radar ranging system

There are several characteristics required of the modulation waveform. One is that it be continuous and periodic with a period long compared to the round trip time or at least compared to the *a priori* uncertainty in the round trip time. A second, is that it must be structured so that it is possible to measure the phase very accurately in order to achieve high range resolution.

These characteristics can be obtained in a binary waveform derived from a pseudo-random sequence. A pseudo-random sequence is a sequence of binary digits which has certain random properties. The sequence is converted to a waveform by assigning a period of time called a digit period to each digit and causing the waveform to have a unit positive value when the corresponding digit is a ZERO and a unit negative value when the corresponding digit is a ONE. The sequence is repeated to make an indefinitely long periodic waveform called a *ranging code.*

The random properties of importance to ranging can be described by the autocorrelation function of the waveform. An example of a pseudo-random sequence, the corresponding waveform, and the autocorrelation function of the waveform are shown in Fig. 10. The interesting feature of the autocorrelation function is that,

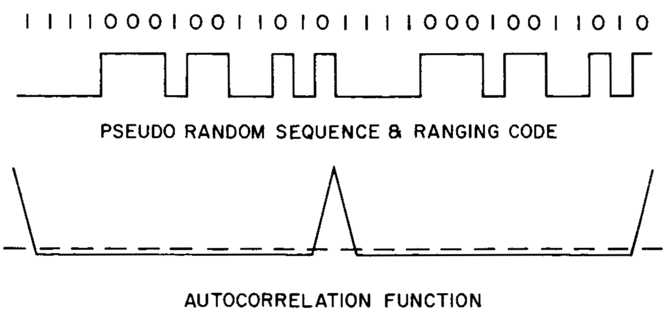

Fig. 10. Ranging code

$$P_1 = 23 \ \mu\text{sec}$$
$$P_2 = 31 \ \mu\text{sec}$$
$$P_3 = 47 \ \mu\text{sec}$$
$$P_4 = 103 \ \mu\text{sec}$$
$$P_5 = 127 \ \mu\text{sec}$$
$$P_1 + P_2 + P_3 + P_4 + P_5 = 331$$
$$P_1 \times P_2 \times P_3 \times P_4 \times P_5 = 438{,}357{,}391$$
$$\text{MAXIMUM RANGE} = 65 \times 10^6 \ \text{km}$$

Fig. 11. Components in a ranging code

for all the values of τ which differ from a multiple of the period by more than one digit period, the value of the autocorrelation function is uniformly low. This implies that the phase of the returned modulation in the ranging system can be determined to within one digit period of the ranging code by crosscorrelation of the returned modulation with a local model of the code. Since a digit period of 1 μsec is typically used, the phase can be determined to within 1 μsec or the range to within 150 m. (Ways will be described later to increase the resolution without decreasing the digit period.)

It has been tacitly assumed that the wave period of the ranging code is of sufficient length to resolve the *a priori* uncertainty in range. It turns out that this is no problem, since it is possible to generate codes whose periods are many hours long even with 1 μsec digit periods. Therefore, a ranging code derived from a pseudo-random sequence fulfills our first two requirements: it can have a period as long as needed and the phase can be measured to within one digit period irrespective of the period of the code.

It turns out that there are some additional requirements. Since the systems under discussion measure very long ranges, the returned signal is weak and the individual digits in the code cannot be recovered from the noise. The phase of the returned signal is determined by a series of trail crosscorrelations between the returned code and a locally generated model of the code. If the local model has the same phase as the returned code, there is a correlation which is detected. If not, the lack of correlation is also detected, but no information is gained as to what the correct phase might be. If the code is very long, a great many trial correlations might have to be made before finding the correct phase. For example, if a code derived from a sequence of length one million were used and there were no *a priori* information about the phase of the returned code, a half-million trial correlations on the average would be required to find the correct phase. This number can be significantly reduced by forming the required long ranging code as a combination of a number of shorter codes. If several continuously repeating pseudo-random sequences with relatively prime periods are combined digit by digit according to any nontrivial Boolean function, the period of the resulting combined sequence is equal to the product of the periods of the component sequences. Furthermore, if the correct Boolean function is chosen for combining the sequences, the crosscorrelation function of the code derived from the combined sequence and a code derived from any one of the component sequences is periodic with the period of the component, has a peak when the component code is in phase with the component in the combined code, and has a uniformly low value when they are out of phase by more than one digit period. If such a combined code is used for ranging, the phase of each component can be determined by cross-correlating with the component code. Since the phase of the combined code is uniquely determined by the phases of the components, a number of trial correlations equal to the sum of the lengths of the component sequences need be performed in order to select the correct phase from among a number equal to the product of the lengths of the component sequences. An example of components which might be used in a ranging code is shown in Fig. 11 where the p_i are the periods of the several components.

The final requirement of the ranging code is that it must be capable of being tracked by the receiver. This is accomplished by including a component in the code which is called a clock. A clock is a code derived from a sequence of alternating ZEROS and ONES. The tracking portion of the receiver is shown in simplified form in Fig. 12. The received signal is a ranging code multiplied by a clock. The two signals have the same digit period so that the product is also a binary waveform with the same digit period. If the code from the code generator is the same as the incoming code and has the same phase,

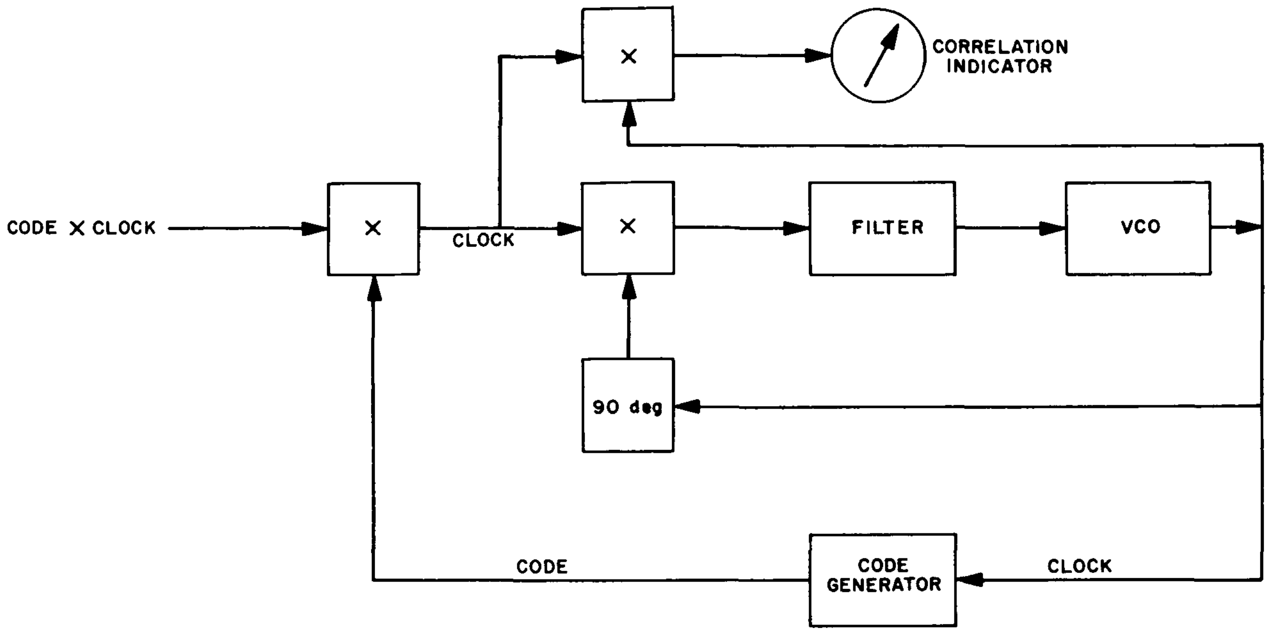

Fig. 12. Double loop code tracking system

the output of the first multiplier will be a clock. The inner loop is a phase-locked loop which locks to a clock and whose output times the code generator. If the phase of the incoming signal tends to change, the inner loop tracks the change in the phase of the clock and causes the outer loop to follow the phase of the code.

Thus, the double loop tracks the incoming code signal. If the code from the code generator is not in phase with the incoming code, the double loop system is used to acquire the incoming code, i.e. determine its phase by a series of trail crosscorrelations. The incoming code is structured so that it has a clock component which can be immediately acquired by the inner loop (Ref. 5 and 6). This structure assures that the phase of the code from the code generator will stay constant relative to the phase of the incoming code and, in particular, that their digit periods coincide. The code generator may then be manipulated so that its output is one of the components and the several phases of the component are produced one after the other. The first multiplier has a clock output whenever the two codes are the same, or more generally whenever the two codes are correlated.

Thus, the clock output is larger when the component code from the local code generator is in phase with the component in the incoming code than when it is not. The amplitude of the clock component and, therefore, the value of the crosscorrelation, is determined by the upper multiplier (synchronous detector). Since the several phases of the component code are almost orthogonal, the theory developed for block telemetry codes applies to the acquisition procedure, and the time required for acquisition can be computed along with the corresponding probability of error (Ref. 7-9). If automatic machinery is used to conduct the acquisition instead of a person reading the meter and controlling the coder, the acquisition can be done very quickly, typically a few seconds or tens of seconds for a radar designed to operate out to lunar distances. The theory has been fully checked by running a million and a half acquisitions under carefully controlled laboratory conditions (Ref. 10).

V. RANGE MEASUREMENT WITH A COHERENT CW RADAR

The basic range measuring system described in the last section was applied to a bistatic radar used to track the Echo I and the Courier satellites in the latter part of 1960 and the early part of 1961 primarily to test the fundamental concepts. Although the system did not contain all of the refinements later developed, for example automatic machine control of the acquisition process, all the basic aspects of the technique were used and the correctness of the whole approach was demonstrated. Useful tracking data were obtained on three consecutive passes of the Courier satellite on January 31, 1961. Angle and doppler data were obtained from all three passes, range data only from the first and third.

To evaluate the ranging data, an orbit was computed from the angle and doppler data of the three passes. The range was computed from the orbit and compared to the measured range. The range measured varied from 1,900,000 to 2,400,000 m with an average discrepancy between the range from the orbit and the measured range of about 20 m. This discrepancy includes the effect of all the inaccuracies in the measurement of angle and doppler as well as all of the shortcomings in the orbit computation process. The good results obtained from this experiment together with a careful analysis of the probable sources of error led to the conclusion that if the technique were applied to spacecraft the range could be measured to within 15 m at lunar distances and to within 50 m at planetary distances. Accordingly, development of equipment and techniques was continued to produce a spacecraft system which is to have its first application in the *Mariner C* mission in late 1964.

The ranging system for spacecraft makes use of the same basic radar and transponder that have already been described in connection with the doppler measurements. There are two types of ranging channels which may be used in the transponder, one for short ranges (out to lunar distances), the other for long ranges (out to planetary distances). In the first type (Fig. 13), called a turnaround transponder, the ranging modulation is synchronously detected, amplified by a video amplifier, hard limited to maintain a constant signal level from the video amplifier even when only noise is present, and used to modulate the returned carrier. This is a particularly simple way to handle the transponding of the ranging signal, since it requires no manipulation of the codes or determination of their phases in the spacecraft. The limitation of this approach is that the signal used to modulate the returned carrier has noise in it from an RF bandwidth of approximately 3 Mc. As the signal level into the transponder decreases, the signal-to-noise ratio at the output of the limiter decreases. The presence of noise at the output of the limiter is not harmful in itself, but, because the limiter output has constant power, it reduces the power in the ranging modulation on the returned carrier. When the modulation power on the returned carrier becomes too low for the ground receiver

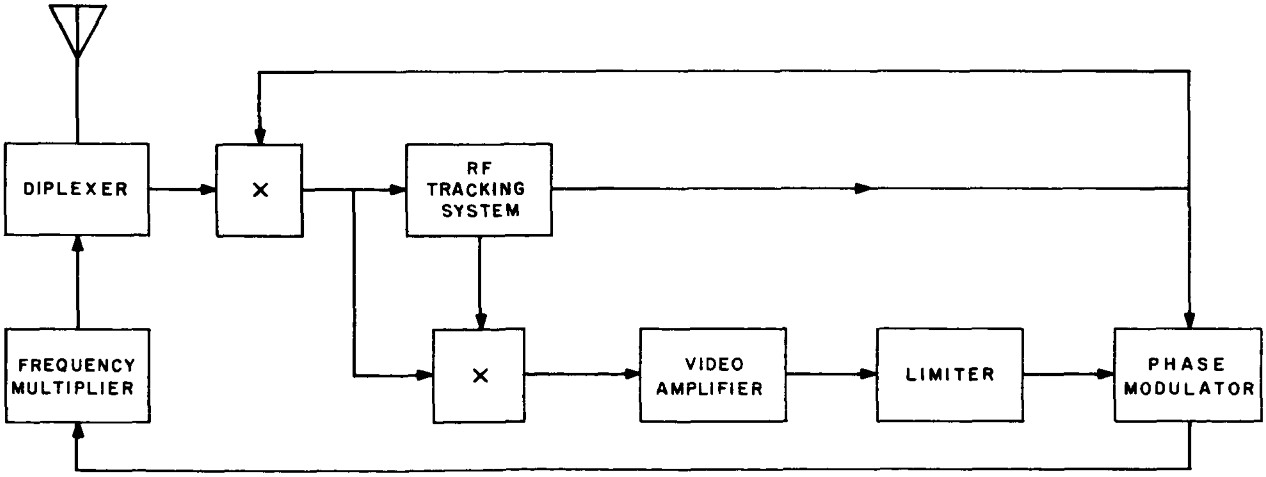

Fig. 13. Turnaround transponder

to acquire and track the system will not operate. Normally, this occurs long before the noise modulation on the returned carrier causes any effect because the bandwidth of the noise is very wide compared to the bandwidth of the ground receiver.

The ground receiver used with the transponder is shown in Fig. 14. The particular frequencies given are those for the NASA/JPL DSIF, but the technique is not dependent on the frequencies used. There are several aspects of this receiver which have not been discussed. First, the double loop code tracking system is somewhat different from that shown in the previous section. The overall form is the same and functionally the loop performs the same operations but the first multiplier is a mixer at the second IF frequency rather than a multiplier at DC. The received signal goes into this mixer as a phase modulated signal at 10 Mc. The local code balance modulates the 10-Mc reference to the mixer. The mixer performs two operations simultaneously; the 10-Mc signal is synchronously detected and the received code is multiplied by the local code. The output of the mixer is a clock whose amplitude is proportional to the correlation between the two codes. This technique has the very great advantage of not requiring a multiplier with a wide band input and DC output. Since the mixing is done at low signal levels, problems of linearity and noise handling are not severe. The clock amplifier is used to provide additional gain comparable to that of the second IF amplifier in the main receiver channel. However, the amplifier is narrow band so that the phase and amplitude detectors which follow it are not subjected to wide band noise. Their outputs are DC but their signal levels are high enough to overcome noise (Ref. 11).

The clock switch loop is part of the mechanism for measuring the phase between the codes. It allows the timing for the transmitter code (the code used to modulate the transmitter) to be derived either from the master frequency standard or from the voltage controlled oscillator (VCO) in the clock tracking loop. When the timing is derived from the VCO, both the transmitter code and

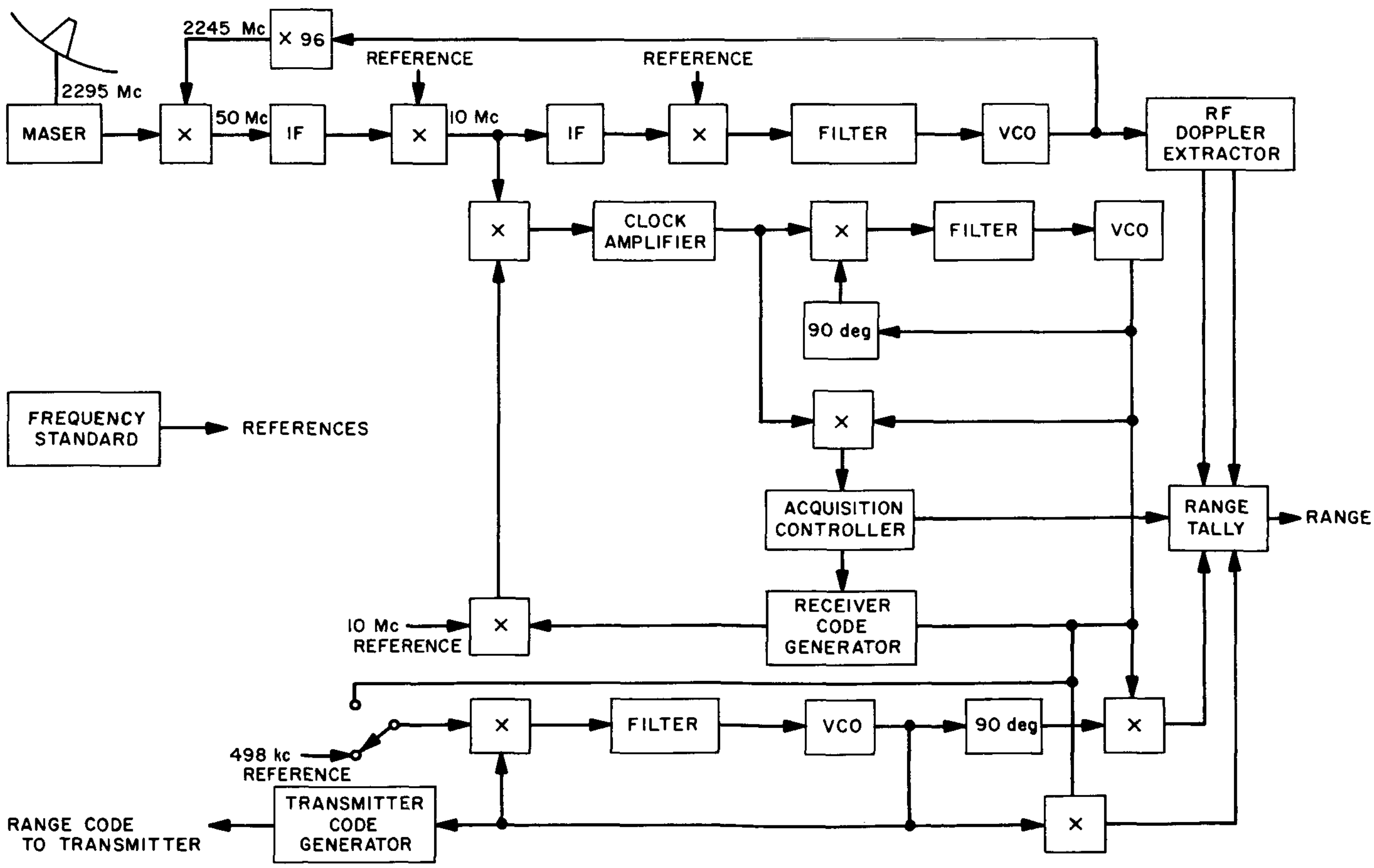

Fig. 14. Ranging receiver

the receiver code (the code which is used in the code tracking loop) have the same timing and may be synchronized. At this time, the phase between the codes is zero and the phase counting device, called the range tally, is set to zero.

If the switch loop is changed to obtain its input from the frequency standard, the timing for the two codes will, in general, be different and a phase difference will accumulate. The clock doppler system is used to determine this phase difference. For each two-digit periods of phase difference between the codes the phase difference of the respective clocks is 1 cps. For each two-digit periods of phase difference between the two codes the output of each clock doppler detector varies through 1 cps of a sinusoid. Since there are two clock doppler detectors the direction of the phase difference can be determined and the range tally keeps a running sum of the phase difference between the codes. Once the receiver has acquired the clock, the change in phase is because of the two-way doppler, hence the name doppler detector. During the acquisition process the several components of the receiver code are stepped in phase by some integral number of digit periods to bring them into phase with the components of the received code. All of these changes in phase are accumulated by the range tally while it also keeps track of any changes due to doppler. When the received code has been acquired, the receiver code is in phase with it and the range tally has an accumulation of the net phase difference between the transmitter code and the receiver code and hence a total of the round trip propagation time (Ref. 12 and 13). As the range changes, the range tally is kept up to date by the inputs from the clock doppler detectors.

The clock doppler detectors are able to provide an input to the range tally whenever the round trip path changes by one quarter of a clock wavelength which is equivalent to a change in range of 75 m for a 1 μsec digit period. However, the clock tracking loop is able to follow the average phase of the clock with an accuracy of a few meters. To achieve a resolution which is commensurate with the accuracy, use is made of the fact that the transmitted code is coherent with the transmitted carrier, i.e. both are derived from the same oscillator. This means that there is a fixed relationship between the doppler on the returned carrier and the doppler on the returned code. For each cycle of clock doppler there are some fixed number of RF doppler cycles. Once the received code has been acquired, the range tally increases the resolution of the range measurement by counting RF doppler cycles instead of clock doppler cycles. Ordinarily the resolution which would be obtained from the doppler on the carrier itself is not required so the doppler on some IF is used instead. In the system shown in Fig. 14, the doppler on the IF at 143.4 Mc is used to give a resolution of 1.04 m.

The system just described is to be used on *Mariner C*. Both the transponder and the ground system have undergone extensive tests in the laboratory and in simulated flights, using helicopters. The specifications for the system call for an overall accuracy of the range measurement of 15 m, but laboratory and helicopter tests achieved an accuracy of better than 2 m (Ref. 14).

The capability of the system can be extended to longer ranges by reducing the bandwidth of the ranging channel in the transponder. This is done by incorporating a full ranging receiver complete with coders in the transponder as shown in Fig. 15. Such a transponder is called a *planetary transponder* since it is designed to operate at planetary distances. The advantage of the planetary transponder is that it has a very narrow noise bandwidth in the ranging channel, typically 1 or 2 cps in contrast to the 3 Mc for the turnaround transponder. This is because the only noise which goes through the channel is that which passes the clock tracking loop in the double loop system. The disadvantage is that the code must be acquired in the transponder as well as on the ground. The acquisition procedure is involved, but makes use of the fact that if the code is acquired on the ground first, the *a priori* knowledge of the range allows the determination of the phase of the codes in the transponder. The phase of the code which modulates the ground transmitter can then be adjusted so that when the code arrives at the transponder, it will have about the correct phase. If the phase of the ground transmitter code is then slowly varied, the transponder code tracking system locks when the code arriving at the transponder passes through the correct phase. The disadvantage is primarily in the increased manipulation required and, of course, the increased complexity in the transponder. The requirement for *a priori* knowledge of the range does not ordinarily pose a problem because once a spacecraft has been tracked to planetary distances, its position is quite well known and the purpose of day-to-day tracking is only to refine that knowledge.

The accuracy of the planetary transponder system is not quite as good as the accuracy of the turnaround transponder system. This is not because of the greater distances involved (the accuracy is independent of the distance), but because there are two racking loops in the

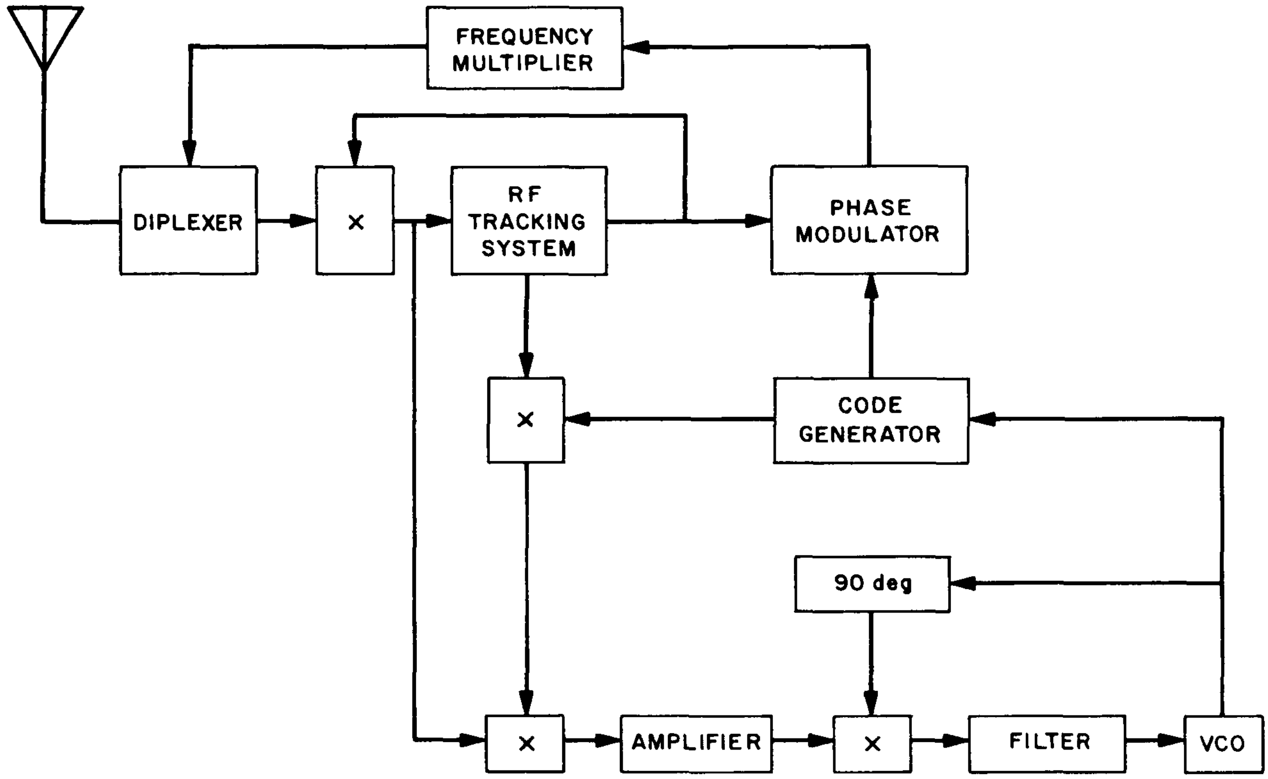

Fig. 15. Planetary transponder

round trip path instead of one. Also, a loop aboard the spacecraft cannot be built as well or kept in adjustment. Careful analysis backed up by extensive laboratory testing indicates that 50 m is a conservative estimate of the accuracy of measurements and present radar system capability would allow such measurements to be made to anywhere in the solar system at least out to the orbit of Mars.

VI. RANGE MEASUREMENT WITH A NONCOHERENT CW RADAR

The methods already described can be extended to measure range with a noncoherent CW radar. As discussed, the noncoherent radar receiver does not track the returned carrier but relies on a programmed local oscillator to continuously tune the receiver and, in the monstatic case, a programmed range keyer to control the time sharing of the antenna between the transmitter and the receiver.

One of the simplest ways of measuring range with such a radar is shown in Fig. 16. The transmitter reference signal is phase modulated by a ranging code to an angle such that, after the frequency multiplication in the transmitter, the carrier is balanced modulated. Since the receiver does not track the carrier no power need be reserved for it; all of the power may be put into the modulation. Similarly the LO signal which is applied to

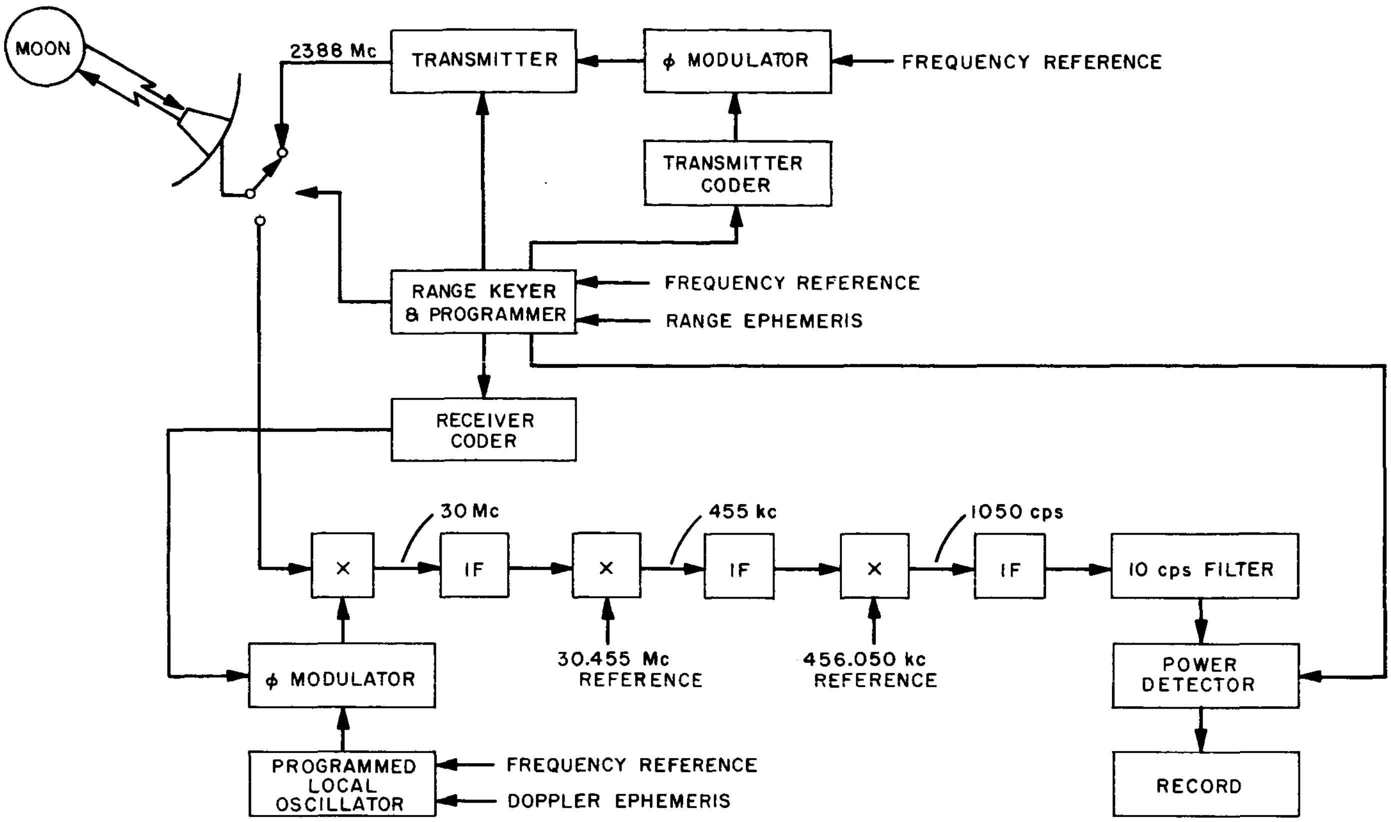

Fig. 16. Open loop noncoherent ranging system

the first mixer in the receiver is also balanced modulated by a ranging code that is programmed to have the proper phase angle relative to the transmitter code according to the range ephemeris. If the target were a *point* target and both the range and doppler ephemerides were correct the output of the first mixer in the receiver would be an unmodulated carrier at the IF frequency. After amplification and heterodyning, the signal is filtered through a narrow band filter and power detected. The power detector includes an integrator and the average power is recorded. In the case of a large target such as the Moon, the returned signal may be considered to be composed of many components, each with a phase difference in the modulation proportional to the distance it has traveled, and a doppler shift on the whole signal due both to the motion of the entire target (Moon) relative to the tracking station and to the rotation of the target as seen from the tracking station. The programmed local oscillator removes the doppler due to the relative motion of the entire target. If the programmed receiver code is adjusted to have the phase of the code returned from the nearest part of the Moon (the front cap), that code will cause an output from the first mixer which is proportional to the power in that portion of the signal and which is at the first IF frequency. A signal which returns from any other part of the target will, because of the correlation properties of the code, cause an output from the first mixer which is at least as wide band as the original modulated signal and which has a doppler shift in addition. The recovered signal from the front cap will pass through the narrow band filter and be detected, signals from other parts will not.

In the discussion so far, it has been assumed that the range ephemeris is perfectly correct in which case there is no need to make a measurement. Of course, it is not perfectly correct. To obtain useful data the ephemeris is assumed to be correct and the power returned from the target at the ephemeris distance, with an appropriate integration time, is measured. The radar is operated as a Dicke radiometer by means of switching not shown in the figure. The range programmer is then adjusted to cause the receiver code to be offset from the ephemeris position by one digit period and the run repeated. In our case when operating on the Moon the ephemeris turns out to be a little short so that no power is measured on the first run and the adjustment is made for the second run to offset the receiver code so as to increase the phase difference with respect to the transmitter code. This process is continued until the front cap is reached and usually a number of steps beyond. Each step beyond measures the power from what is called a range zone, which is a ring centered on the front cap.

The system which has been used at JPL on the Moon uses a 1 μsec digit period so that each range zone is 150 m deep. The front cap is approximately 40 km in dia or 1250 sq. km. By the properties of a sphere all range zones have the same area (Ref. 15). There seems to be no doubt that the measurements are at least that accurate. The problem of using such measurements to improve the ephemeris is severe because of the local relief, which may be several km, and the irregularity of the figure of the Moon.

A similar system has been used to track the planet Venus. Since Venus is much farther away than the Moon, the range gate was widened to recover more power by admitting returns from a larger area. The digit period most used was 125 μsec which gives a range zone of 1.875 km depth. Furthermore, the system was arranged to track in range. Note that, because of the *a priori* knowledge of range, a multiple component code is not required and no clock is needed for the open loop system used on the Moon. The tracking system used on Venus also dispenses with the clock and makes use of the shape of the scattering law for reflections from the planet. If the range gate were moved continuously across the front face of the planet, it would be observed that the power measured by the power detector in Fig. 15 would first increase as more and more of the range zone was on the planet but as soon as the entire range zone was on the planet further movement would cause the power to decrease because the normal to the area from which the signal was being returned would be at an increasing angle to the line of sight. Thus, if there were two adjacent range zones, they could be adjusted to have equal returned power by having the one partially in front of the front cap and the other into the planet far enough to be past the peak of the reflection characteristic. Such a pair of range zones could be made to track the planet by comparing the power and causing both zones to move out of the planet if the power in the first zone is greater than in the second and vice versa. This is the scheme that is used except that the two measurements are not made simultaneously. The power is measured first in one zone and then in the other. A comparison is made, and, if the power is not the same, the phase of the receiver code is adjusted. It is not necessary to operate the receiver as a radiometer since the noise is automatically subtracted out in the comparison process. The block diagram for the system is the same as that in Fig. 15, except that the output of the power detector is fed back into the range programmer which includes a stored program machine capable of performing the necessary computations and controlling the receiver coder accordingly. Since the antenna is time shared, it is not available to the receiver half the time. During these intervals the range rate is extracted from the ephemeris to continuously adjust the phase of the receiver coder. During the time that the receiver is available the ephemeris rate is still used to help adjust the phase of the receiver coder.

The system just described was used during May, June, and July of 1964 to track the planet Venus (Ref. 16). Typical runs were for 2 hr of which half the time was receive time. The noise on the range measurement was typically 5 km peak-to-peak. The residuals of the range compared to the ephemeris over a 12-day period were used to determine a straight line. The rms variation of the residuals about the line was 2 km.

VII. SUMMARY

A number of methods by which a CW radar may be used to measure radial velocity and range have been presented. Experience has shown that, if the returned signal is coherent and strong enough to be tracked by a phase-locked loop receiver, a CW radar can determine the radial velocity to a fraction of 1 cm/sec. If the returned signal is not coherent or the signal is not strong enough to be tracked by a phase-locked loop receiver, but there is a reasonably good ephemeris for the target, the radial velocity can be determined to a few centimeters per second. The noncoherent method has so far been applied only to passive targets but could certainly be applied to spacecraft.

Range measuring experiments with passive targets combined with extensive laboratory and helicopter experiments indicate that accuracies of 15 m can be achieved if the returned signal is coherent and the target is either small and passive or uses a simple turnaround transponder. Of course, the signal must be strong enough so that the carrier can be tracked by a phase-locked loop receiver. If the distance is great enough so that a planetary transponder with a range tracking loop is required, an accuracy of 50 m should be achievable.

Techniques for measuring range when the returned signal is noncoherent have so far been applied only to celestial bodies. The accuracies achieved, 150 m for the Moon and 2 km for Venus, were limited primarily by the roughness of the target and the digit period needed to obtain the necessary reflecting surface on the target. Certainly higher accuracy could be achieved with a small target or with transponding spacecraft.

The several methods which have been described have all been mechanized and tried by actual experiment. They represent the present state of the art and show that it is, in fact, well developed. However, none of the techniques has yet run into any fundamental limitation, such as variation in propagation velocity or opacity in space, which limits its accuracy or the distance over which it may be used. It is, therefore, safe to say that the techniques presented will be developed further and new ones found.

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